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Letter to the Editor

On the optical counterpart of NGC 300 X-1 and the global Wolf-Rayet content of NGC 300*

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ABSTRACT

Context. Surveys of Wolf-Rayet (WR) populations in nearby galaxies provide tests of evolutionary models plus Type Ib/c supernova progenitors. This spectroscopic study complements the recent imaging survey of the spiral galaxy NGC 300 by Schild et al.
Aims. Revisions to the known WR content of NGC 300 are presented. We investigate the WR nature of candidate #41 from Schild et al. which is spatially coincident with the bright X-ray point source NGC 300 X-1.
Methods. VLT/FORS2 multi-object spectroscopy of WR candidates in NGC 300 is obtained.
Results. We establish an early-type WN nature of #41, i.e. similar to the optical counterpart of IC 10 X-1, which closely resembles NGC 300 X-1. We confirm 9 new WR stars, bringing the current WR census of the inner disk to 31, with N(WC)/N(WN)~0.9.
Conclusions. If #41 is the optical counterpart for NGC 300 X-1, we estimate a WR mass of 38 $M_\odot$ based upon ground-based photometry, from which a black hole mass of $\geq$ 10 $M_\odot$ results from the 32.8 hr period of the system and WR wind velocity of 1250 km s^{-1}. We estimate an 95% completeness among WC stars and 70% among WN stars, such that the total WR content is ~40, with N(WC)/N(WN)~0.7. From the Hα-derived star formation rate of the inner galaxy, we infer N(WR)/N(O)~0.04.

Key words. galaxies: NGC 300 – stars: Wolf-Rayet – X-rays: binaries – X-rays: individuals: NGC 300 X-1

1. Introduction

Massive stars dominate the feedback to the local interstellar medium (ISM) in star-forming galaxies via their stellar winds and ultimate death as core-collapse supernovae (SNe). In particular, Wolf-Rayet (WR) stars typically have wind densities an order of magnitude higher than massive O stars. They contribute to the chemical enrichment of galaxies, they are the prime candidates for the immediate progenitors of long, soft Gamma Ray Bursts (GRBs), and they provide a signature of high-mass star formation in galaxies (Crowther 2007).

WR stars exhibit a unique broad emission line spectral appearance, for which He II λ4686 (WN subtypes) and C III λ4647-51, C IV λ5801-12 (WC subtypes) provide the basis for their detection in external galaxies. Narrow-band filter techniques have been developed by Moffat, Seggewiss & Shara (1985) and Massey, Armandroff & Conti (1986) and applied to Local Group galaxies. Attempts have been made with 4m telescopes to extend the technique beyond the Local Group, although this proved to be challenging for the southern spiral NGC 300 (Schild & Testor 1991) at a distance of 1.88 Mpc (Gieren et al. 2005).

The advent of efficient, multi-object spectrographs at 8m telescopes, such as FORS1/2 at the Very Large Telescope, has permitted surveys of WR populations in galaxies at distances of several Mpc. Such narrow-band surveys – NGC 300 (Schild et al. 2003), M 83 (Hadfield et al. 2005), NGC 1313 (Hadfield & Crowther 2007) – complement ongoing broad-band surveys for SN progenitors (e.g. Smartt et al. 2004). Indeed, WN and WC stars are believed to be the immediate progenitors for a subset of Type Ib (H-poor) and Type Ic (H, He-poor) SN. Progenitors of Type Ib/c SN remain to be established, for which broad-band surveys would fail to confirm the emission-line (WR) nature.

It is well established that the absolute number of WR stars and their subtype distribution are metallicity dependent. N(WR)/N(O)~0.15 in the metal-rich Solar neighbourhood, yet N(WR)/N(O)~0.01 in the metal-deficient SMC (Crowther 2007). This observational dependence results from the easier removal of progenitor O star hydrogen-envelopes at high metallicity, since O-type stars possess winds that are driven by metallic lines (Mokiem et al. 2007). Consequently, the WR content of star forming galaxies spanning a range of metallicities provide useful test cases for evolutionary and population synthesis models (Meynet & Maeder 2005).

In addition, high spatial resolution X-ray surveys of nearby galaxies with *Chandra* and *XMM-Newton* permit the identification of exotic binaries. Carpano et al. (2007a) established that the brightest X-ray point source in NGC 300 X-1 was spatially coincident with the candidate WR star #41 from Schild et al. (2003). Systems involving WR stars and a close neutron star (NS) or black hole (BH) companion represent a natural, albeit rare, end state for close binary evolution, for which only Cyg X-3 in the Milky Way and IC 10 X-1 are confirmed to date (Lommen et al. 2005). Establishing the nature of #41 is the primary motivation for the present Letter, together with a more comprehensive study of the WR content of NGC 300.

2. Observations

We used the ESO Very Large Telescope and Focal Reducer/Low Dispersion Spectrograph #2 (FORS2) in multi-object spec-

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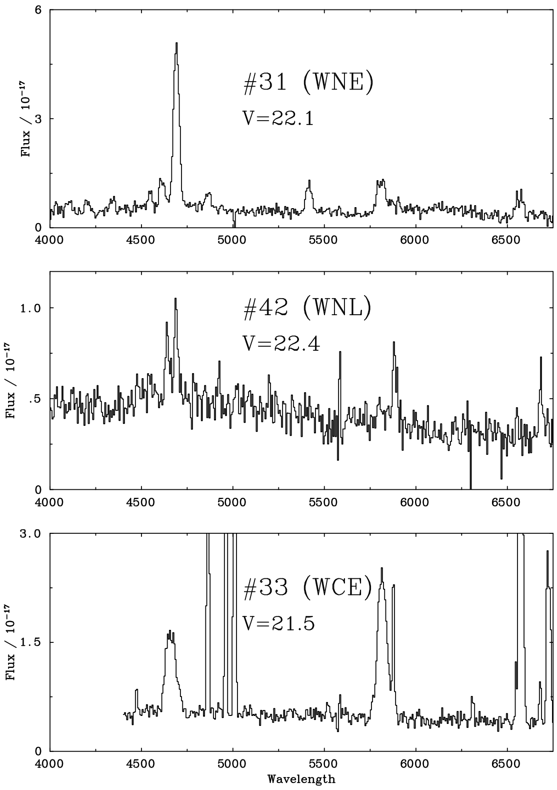

Fig. 1. VLT/FORS2 spectroscopy of three new WR stars. Narrow emission lines in the spectrum of #33 are from an associated H II region.

troscopy (MOS) mode on 12 Jan 2007 using three 800 s exposures with the 300V grism, centred at λ=5900Å. 16 WR candidates from Schild et al. (2003) were observed simultaneously using MOS with 1.0 arcsec slits, of which 4 sources had previously been spectroscopically confirmed. Seeing conditions were 1.1–1.2 arcsec at relatively high airmass of 1.7–2.0.

A standard extraction was performed using IRAF, with wavelength and flux calibration carried out using FIGARO. The spectral resolution, as measured from comparison arc lines was ~10Å. The flux standard LTT 1788 provided a relative flux calibration. Flux calibration of #9, #24, #30 and #40, in common with spectroscopy of Schild et al. (2003), were found to be in excellent agreement. Absolute flux calibration was achieved by comparing the photometry of an individual object in the λ4684 filter (from Schild et al. 2003) with a synthetic photometric measurement, determined by convolving our spectroscopy with a suitable Gaussian filter and zero-point.

3. Wolf-Rayet content of NGC 300

Of the 12 new WR candidates we can confirm 9 cases, including #41 (NGC 300 X-1), for which we defer a detailed discussion until the next section. A summary of our new VLT/FORS2 spectroscopic detections is presented in Table 1, with three new WR stars shown in Fig. 1. Of the remaining candidates, #20 was established as a foreground late-type star, #27 was identified as an Of star with weak, narrow He II λ4686 emission (#8 possessed weak broad emission). Candidate #23 did not include the critical λ4686 region, so a WC nature was excluded.

For the inner disk of NGC 300, our results decrease the observed N(WC)/N(WN) ratio from 1.2 (12/10) to ~0.9 (15/16).

Table 1. List of Wolf-Rayet candidates from Schild et al. (2003) spectroscopically observed with VLT/FORS2, $\Delta m = m_{4781} - m_{4686}$. Candidate #41 is spatially coincident with NGC 300 X-1.

ID	m_{4781}	Δm	C III 4650/He II 4686		C IV 5808		Sp.Type
	mag	mag	W_λ (Å)	FWHM (Å)	W_λ (Å)	FWHM (Å)	
3	23.13	1.25	110±6	24±1	–	–	WNE
5	22.61	2.09	44±1	40±1	28±2	35±2	WCE
8	20.46	0.22	3±1	17±3	–	–	WNL
12	22.44	1.57	148±5	30±1	–	–	WNE
20	18.65	0.11	–	–	–	–	Not WR
23	19.80	0.08	–	–	–	–	Not WC
27	20.54	0.15	3±1	10±2	–	–	Of
31	22.42	1.68	216±7	34±1	–	–	WNE
33	22.30	1.02	149±6	66±2	266±5	58±1	WCE
41	22.59	0.95	53±3	19±1	–	–	WNE
42	22.58	0.56	17±3	19±4	–	–	WNL
52	22.66	0.50	397±18	74±3	590±20	83±3	WCE

Our results provide WR statistics for 30 sources versus 21 in Schild et al. (2003), recalling that #11 hosts both WN and WC stars. At face value, our study is merely an incremental step, since sources are drawn from a sample of 58 candidates within a de-projected radius of 5 arcmin (3 kpc). However, excluding #20 and #23, Fig. 2 shows that there are only 5 additional candidates with a photometric excess greater than 0.3 mag. Excesses of the remaining 21 cases are as little as 0.08 mag.

Sources with large photometric excesses are likely to be WC stars on the basis of their intrinsically stronger emission lines (cf. Fig. 1). Indeed, all 4 spectroscopically confirmed WR stars with photometric excesses greater than 2 mag are WC stars (recall Fig. 2). Sources with small photometric excesses will either be foreground late-type stars, Of stars or genuine WN stars. Assuming that #37 is a WC star, with WN subtypes for all other candidates in excess of 0.15 mag, and otherwise either an Of star or foreground late-type star. Consequently, the true WR content of the inner disk of NGC 300 is likely to increase from 31 to ~40, with a subtype ratio closer to N(WC)/N(WN) ~ 0.7. We compare the observed (filled symbols) and anticipated (open symbols) WR subtype distributions in NGC 300 and NGC 1313 (Hadfield & Crowther 2007) with spectroscopic results for other nearby galaxies in Figure 3, together with evolutionary predictions from Meynet & Maeder (2005) and Eldridge & Vink (2006). High N(WC)/N(WN) ratios for metal-rich galaxies support the latter models, which allow for metallicity-dependent WR winds (Crowther 2007).

The observed WC subtype distribution of relatively metal-poor galaxies, with log (O/H) + 12 ≤ 8.5, is known to be dominated by early-type WC stars, e.g. such as the LMC and IC 10 (e.g. Crowther et al. 2003). In contrast, more metal-rich galaxies with log(O/H) + 12 ≥ 8.5 will possess a fraction of late-type WC stars, as is the case for M 33, M 31 and the Milky Way. In the extreme metal-rich environment of M 83, with log(O/H) + 12 ~9, late subtypes dominate the WC population (Hadfield et al. 2005). Of the 15 known WC stars within the inner disk of NGC 300, all are early-types, i.e. the WC population is more in common with other metal-poor galaxies. However, the average metallicities of four H II regions (within $\rho/\rho_0 \leq 0.5$) from Pagel et al. (1979) and Webster & Smith (1983) is log(O/H) + 12 = 8.62, close to the currently adopted Solar oxygen abundance of 8.66 (Asplund et al. 2004).

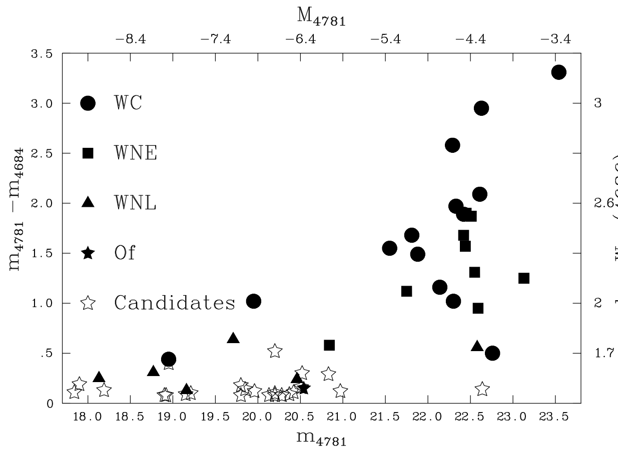

Fig. 2. Comparison between the λ4781 continuum magnitudes of WR candidates in NGC 300 and the λ4684 excess (stars), updated from Schild et al. (2003). Spectroscopically confirmed WR stars are presented – see key. *Approximate* absolute magnitudes and line equivalent widths are indicated. Three WR candidates, #1 (WC4), #37 and #51, for which reliable photometry was not feasible are omitted from this figure.

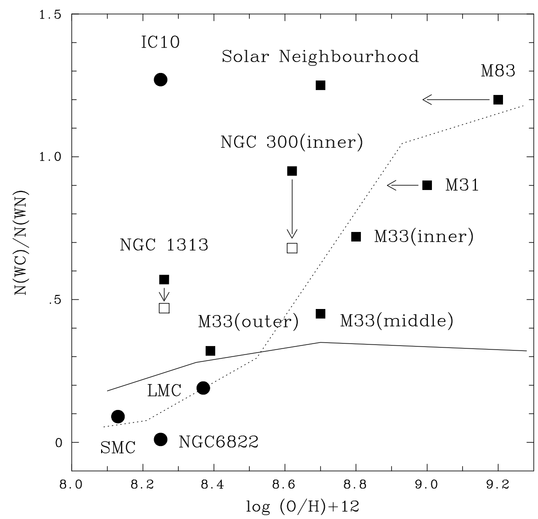

Fig. 3. Spectroscopically confirmed N(WC)/N(WN) ratio for NGC 300, together with other nearby spiral (filled squares) and irregular (filled circles) galaxies from Crowther (2007) and references therein, plus Hadfield & Crowther (2007) for NGC 1313. Open symbols for NGC 300 and NGC 1313 are corrected for candidate WR sources, as outlined in the text. Predictions from Meynet & Maeder (2005, solid) and Eldridge & Vink (2006, dotted) are also shown.

The O star content of NGC 300 can most readily be obtained from Hα imaging. Deharveng et al. (1988) provide a catalogue of H II regions, including Hα fluxes, the total output of which is 1.3 $\times 10^{-11}$ erg s^{-1} cm^{-2}. Correction for a typical extinction of $c(H\beta)$ = 0.21 from Webster & Smith (1983) implies a Hα luminosity of 7.8×10^{39} erg s^{-1} adopting the Gieren et al. (2005) distance to NGC 300. A global star formation rate (SFR) of 0.06 $M_\odot$ yr^{-1} is implied for NGC 300, adopting the Kennicutt (1998) calibration. A somewhat higher Hα SFR of 0.11 $M_\odot$ yr^{-1} was presented by Helou et al. (2004), adjusted for the Gieren et al. (2005) distance. For our study, we adopt an intermediate global SFR of 0.085 $M_\odot$ yr^{-1} – a factor of two higher than the Small Magellanic Cloud (SMC, Kennicutt et al. 1995) – from which a Lyman continuum ionizing output of 8×10^{51} is inferred. From Kennicutt (1998) this is equal to 1,400 O7 V equivalents based upon an O7 V ionizing output of $10^{48.75}$ (Martins et al. 2005).

Of course for a realistic N(WR)/N(O) ratio, we need to consider that Schild et al. (2003) surveyed the inner galaxy of NGC 300 (recall their fig. 1). From Deharveng et al. (1988) $\sim$78% of the Hα flux lies within this region, i.e. 1,100 equivalent O7 V stars. As such, we obtain N(WR)/N(O)$\sim$0.04 on the basis of $\sim$40 WR stars. This is intermediate between that observed in the low metallicity SMC for which N(WR)/N(O)$\sim$0.01 and the Solar neighbourhood for which N(WR)/N(O)$\sim$0.15 (Crowther 2007). Again, the N(WR)/N(O) distribution suggests a metallicity that is 0.1 $-$ 0.2 dex more metal-poor than is suggested by Pagel et al. (1979) and Webster & Smith (1983). Modern nebular abundance studies of NGC 300 are underway (Bresolin, priv. comm.), which will permit tests of our assertion that the metallicity of NGC 300 is sub-solar.

4. NGC 300 X-1

One natural, albeit rare, product of close massive binary evolution involves a Wolf-Rayet star plus a compact (NS or BH) companion, if the system survives the core-collapse SN. Until recently, Cyg X-3 in the Milky Way, with a period of 4.8 hr and X-ray luminosity of 10^{38} erg s^{-1}, was the only known example of an X-ray bright WR plus compact companion system (van Kerkwijk 1993). Lommen et al. (2005) discuss the possible origins of Cyg X-3, namely the accretion disk associated with a BH, fed by a massive WR star, or a NS fed through Roche lobe overflow by a lower mass helium star.

Bauer & Brandt (2004) identified IC 10 X-1 as the first candidate extragalactic WR plus compact companion due to its spatial coincidence with the early-type WN star [MAC92]-17A from Crowther et al. (2003) and Clark & Crowther (2004). Recently, Prestwich et al. (2007) identified a period of 34.4 hr for IC 10 X-1 and established large radial velocity variations of the He II λ4686 line, attributable to orbital motion of the WN star, confirming this system as a WR plus BH system.

Carpano et al. (2007a) established that #41 from Schild et al. (2003) is the prime candidate for the optical counterpart of NGC 300 X-1. In Fig. 4 we present VLT/FORS2 spectroscopy of #41, which reveals an early-type WN spectrum. A subtype of WN5 results from the comparable strengths of the N V $\lambda\lambda$4603-20 and N III $\lambda\lambda$4634-41 emission lines.

Spectroscopic similarities between [MAC92] 17-A and NGC 300 #41, reinforced in Fig. 4, further support a common nature. Indeed, NGC 300 X-1 has X-ray properties reminiscent of IC 10 X-1, including a similar period of 32.8 hr (Carpano et al. 2007b). If the early-type WN star #41 is the optical counterpart to NGC 300 X-1, what are its properties? MPG/ESO 2.2m Wide Field Imager photometry from Carpano (2006) suggests V=22.53 mag and B-V = 0.18 mag, the former in good agreement with V=22.44 from Schild et al. (2003). For the 1.88 Mpc distance to NGC 300 (Gieren et al. 2005), we infer $M_V = -5.4$ mag for a reddening of E(B-V)=0.5 mag which results from an intrinsic WR colour of $(B-V)_0$ = -0.32 mag.

We have calculated a representative synthetic model using the Hillier & Miller (1998) line-blanketed, non-LTE model atmospheric code. Relatively simple atomic species are considered in detail, namely H, He, C, N, O, Ne, Si, S and Fe given the poor quality and limited spectral range of the observations.

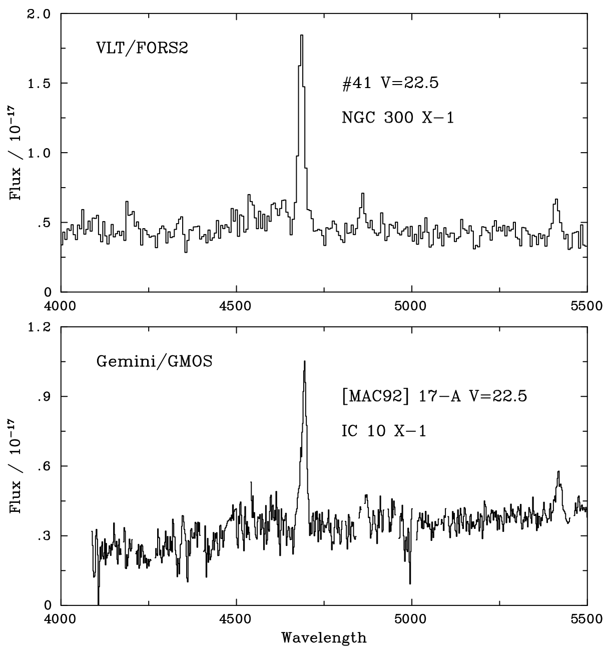

Fig. 4. Spectroscopic comparison between NGC 300 #41, a candidate for the optical counterpart of NGC 300 X-1, and [MAC92] 17-A, alias IC 10 X-1 (Clark & Crowther 2004; Prestwich et al. 2007).

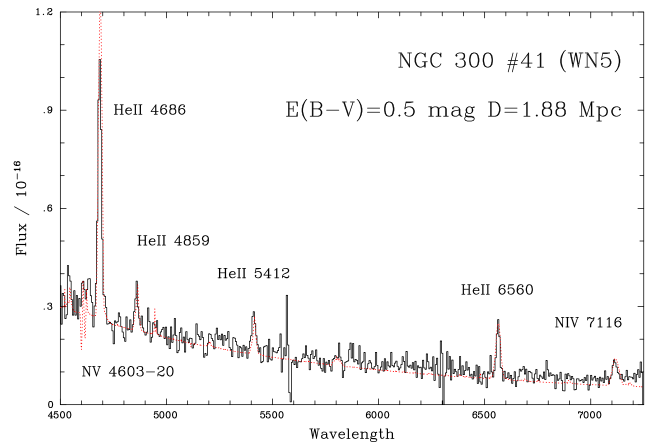

Fig. 5. Spectroscopic comparison between the de-reddened VLT/FORS2 spectrum of NGC 300 #41 and the theoretical non-LTE model (dotted-lines) discussed in the text.

As such, a unique spectral fit may not be claimed, although a model with the following stellar parameters – T_*= 65,000 K, $\log(L/L_\odot)$=6.14, $\dot{M}$=7.5×10^{-6} $M_\odot$ yr^{-1}, v_∞=1250 km s^{-1} – reproduces the observed He II λ4686, 5411, 6560 lines plus N V $\lambda\lambda$4603-20 and N IV λ7116, as shown in Fig. 5. Clumping is accounted for in a crude manner, with a (maximum) volume filling factor of 10%, such that the derived mass-loss rate is equivalent to a homogeneous mass-loss rate of $\sim 2.5 \times 10^{-5}$ $M_\odot$ yr^{-1}.

For a hydrogen-free WN star, one obtains a WR mass of 38 $M_\odot$ on the basis of the Schaerer & Maeder (1992) mass-luminosity relation. Such a high WR mass together with the 32.8 hr period of the system suggests a companion mass ≥ 10 $M_\odot$ (Carpano et al. 2007b, their fig. 6). This follows from the need to form an accretion disk around the BH (Ergma & Yungelson 1998; Lommen et al. 2005), producing the strong X-ray emission. Consequently NGC 300 X-1/#41 shares much in common with IC 10 X-1/[MAC92] 17-A for which Clark & Crowther (2004) obtained a WR mass of 33 $M_\odot$ using similar techniques, and Prestwich et al. (2007) inferred a BH mass of 20–30 $M_\odot$. Consequently, one would expect radial velocity variations of the WR features of order 100–200 km s^{-1}, both to confirm the WR nature of NGC 300 X-1 and establish a robust BH mass. Reduced WR and BH masses would follow if other sources were to contribute to the ground-based photometry of #41. If the WR star is responsible for 50% of the measured flux, its inferred mass would decrease from 38 to 22 $M_\odot$, i.e. closer to the normal WR mass range (Crowther 2007). Consequently, our results would greatly benefit from high spatial resolution optical imaging.

5. Summary

We present new VLT/FORS2 spectroscopy of Wolf-Rayet candidates in the inner disk of NGC 300 from Schild et al. (2003), increasing the census of WR stars within the inner disk to 31, comprising 16 WN and 15 WC stars. After correction for incompleteness, we estimate a true WR content of ~40, with a subtype ratio close to N(WC)/N(WN)~0.7. Curiously, the WC stars in NGC 300 are dominated by early-types, in common with populations in nearby metal-poor galaxies, yet the H II region measured metallicity of NGC 300 appears relatively metal-rich, with log(O/H) + 12 ~8.6. N(WR)/N(O) ~ 0.04 is inferred from the Hα derived global star formation rate of NGC 300, after correction for the ~78% fraction within the inner disk.

We present spectroscopy of candidate #41 from Schild et al. (2003) which reveals an early-type WN5 spectrum, and supports the claim by Carpano et al. (2007ab) that NGC 300 X-1 is the third known WR plus compact companion system identified. If #41 is indeed the optical counterpart of NGC 300 X-1, we estimate WR properties for which we obtain a mass of 38 $M_\odot$. On the basis that an accretion disk is able to form around the compact (BH) component, and so produce strong X-ray emission, Carpano et al. (2007b) suggest a companion mass ≥ 10 $M_\odot$ given the 32.8 hr period of the system.

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